U.S. GODAE: Global Ocean Prediction with the HYbrid Coordinate Ocean Model

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LONG-TERM GOALS

Use the HYbrid Coordinate Ocean Model (HYCOM) with data assimilation in an eddy-resolving, fully global ocean prediction system with transition to the Naval Oceanographic Office (NAVOCEANO) at 1/12° equatorial (~7 km mid-latitude) resolution in 2007 and 1/25° resolution in 2011. The model will include shallow water and provide boundary conditions to finer resolution coastal and regional models that may use HYCOM or a different model. In addition, HYCOM will be coupled to atmospheric, ice and bio-chemical models, with transition to the Fleet Numerical Meteorology and Oceanography Center (FNMOC) for the coupled ocean-atmosphere prediction.

OBJECTIVES

(1) Develop a next generation eddy-resolving, fully global ocean prediction system using HYCOM with 1/12° equatorial resolution. (2) Transition this system to NAVOCEANO for operational use in 2007 with assimilation of sea surface height (SSH) from satellite altimeters, sea surface temperature (SST) and temperature (T)/salinity (S) profiles and the ability to perform skillful 30-day forecasts. (3) Include two-way coupling to an ice model. (4) Ensure that an accurate and generalized ocean model nesting capability is in place to support regional and littoral applications, including the capability to provide boundary conditions to nested models with fixed depth z-level coordinates, terrain following coordinates, generalized coordinates (HYCOM), and unstructured grids. (5) To facilitate this goal, develop HYCOM into a full-featured coastal ocean model in collaboration with a partnering project. (6) Participate in the multinational Global Ocean Data Assimilation Experiment (GODAE) and international GODAE-related ocean prediction system intercomparison projects.

APPROACH

This is a highly collaborative NOPP project with 24 partnering groups listed in the proposal. These partners are universities (with Eric Chassignet at the Florida State University as the overall lead PI), government (Navy and NOAA), industry and international. Additional partnering efforts are listed under related projects. The description of the approach focuses primarily on aspects performed at NRL-Stennis, many in close collaboration with project partners and partnering projects.

1. Ocean model design: HYCOM is a generalized (hybrid isopycnal/σ/z) coordinate ocean model. It is isopycnal in the stratified ocean, but reverts to a terrain-following (σ) coordinate in shallow depths, and to pressure (~z-level) coordinates in the surface mixed layer. The vertical coordinate is dynamic in

space and time via the layered continuity equation, which allows a dynamical transition between the coordinate types. Like the Miami Isopycnic Coordinate Ocean Model (MICOM), HYCOM allows isopycnals intersecting sloping topography by allowing zero thickness layers. HYCOM was developed from MICOM using the theoretical foundation for implementing a hybrid coordinate system set forth in Bleck and Boudra (1981), Bleck and Benjamin (1993) and Bleck (2002). HYCOM was largely developed under an earlier NOPP project in a close collaboration between Rainer Bleck (Goddard Institute for Space Studies), Alan Wallcraft (NRL) and George Halliwell (University of Miami), the lead performer in each group. Alan Wallcraft is in charge of developing and maintaining the standard version of the model, one that is scalable/portable and can run on the latest computer architectures. HYCOM is maintained as a single source code with the maximum feasible backward compatibility.

2. Data assimilation techniques: Primarily, NRL-Stennis is using multi-variate optimum interpolation (MVOI) (Daley, 1991) in the NRL Coupled Ocean Data Assimilation (NCODA) system (Cummings, 2005), which was adapted for use in HYCOM in collaboration with O.M. Smedstad (Planning Systems, Inc.) and C. Thacker (NOAA/AOML). 3DVAR is a planned upgrade to NCODA, which also includes advanced data QC. The primary data types are SSH from satellite altimetry, SST and subsurface T & S profiles. Either the Cooper and Haines (1996) technique or synthetic T & S profiles (Fox et al., 2002) can be used for downward projection of SSH and SST.

3. Ocean model and prediction system configurations: The primary model domain is a fully global HYCOM configuration. It consists of a bipolar Arctic grid matched to a Mercator grid at 47°N. The resolution is .08°cosθ in latitude (θ) south of 47°N by .08° in longitude or ~7 km resolution for each model variable at mid-latitudes and 3.5 km at the North Pole. The array size is 4500 x 3298 with 32 hybrid layers in the vertical. The model is run with atmospheric forcing only and with data assimilation using a large FY05-08 DoD High Performance Computing (HPC) Challenge grant of computer time. A 1/12° Gulf of Mexico HYCOM configuration is the test bed for extensive testing of the NCODA system, including different options and modifications. A wide range of data sets are available for the evaluation (Chassignet et al., 2000; Hurlburt and Hogan, 2000) and these papers discuss many climatological model-data comparisons. In addition, we have long time series of transports through the Florida Straits, sea level at tide gauges, altimetric SSH, SST, subsurface T profiles from BTs and moored buoys, and T & S profiles from ARGO floats, some data obtained routinely and some from research field programs. Bill Schmitz (Woods Hole emeritus) is a part of the evaluation effort.

4. Boundary conditions for littoral and regional models (in collaboration with project partners and related projects): At NRL it includes a nesting capability for (1) HYCOM, (2) the Navy Coastal Ocean Model (NCOM) which allows mixed z-level and terrain following coordinates, and (3) a baroclinic Discontinuous-Galerkin (DG) version of ADvanced CIRCulation (ADCIRC), the latter an unstructured grid model developed at NRL-Stennis for baroclinic coastal/estuarian applications. NCOM is also a component of NRL-Monterey's regional Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS™) (Hodur, 1997) and will be nested in HYCOM within COAMPS. See separate FY07 ONR Report.

5. GODAE: The project will participate in GODAE and the related prediction system intercomparison projects, e.g. the European MERSEA. The purpose of GODAE is to help justify a permanent global ocean observing system by demonstrating useful real-time global ocean products. Consistent with this goal, real-time HYCOM prediction system output is made available to the public via a 100 Tb Live

Access Server (LAS) at Florida State. NRL is represented on the International GODAE Steering Team (IGST) by J. Cummings and H. Hurlburt.

WORK COMPLETED

Three HYCOM NOPP GODAE project meetings were held, one in Tallahassee, FL in November 2006, one at NRL-Stennis in April 2007 and the 3rd in Bergen, Norway following a Layered Ocean Model Workshop in August 2007. J. Cummings and H. Hurlburt represented NRL at the August 2007 IGST Meeting and H. Hurlburt gave two presentations.

A fully-global 1/12° (~7 km mid-latitude) resolution configuration of HYCOM with NCODA data assimilation is running in a pre-operational status at NAVOCEANO using operational queues. It began running daily in near real-time on 22 December 2006 and real-time on 16 February 2007, in near real-time as soon as the new IBM Power 5 at NAVOCEANO was available, and in real-time as soon as regularly scheduled operational queues were established. Thus, it became the first real-time eddy-resolving global ocean prediction system with high vertical resolution. Each day it performs a 5-day hindcast to pick up delayed data and it makes a 5-day forecast. A 30-day forecast capability has also been demonstrated. Real-time and archived results for many subregions can be seen on the HYCOM web page, http://www.hycom.org, including model-data comparisons. In addition, results have been included in a chapter entitled "Eddy-resolving global ocean prediction" (Hurlburt et al., 2007) for an AGU monograph on "Eddy-Resolving Ocean Modeling". In the pre-operational mode, improvements in HYCOM/NCODA and the atmospheric forcing were implemented in the real-time run as soon as they passed testing, as noted below. Here, global HYCOM is always run with thermobaricity using a reference depth of 2000 m for potential density, i.e. in σ_2* mode the vertical.

A new 1/12° global HYCOM simulation with climatological atmospheric forcing (and no ocean data assimilation) was initialized from an ocean climatology near the end of FY06 and continued through FY07. The forcing is based on a more recent ECMWF Re-Analysis (ERA40) (Uppala et al., 2005) with the wind speed scaled using a QuikSCAT analysis from Mark Bourassa at Florida State. It uses the newer bulk formulae of Kara et al. (2005) for wind stress and for the latent and sensible heat fluxes. The forcing was also corrected for land contamination (Kara et al., 2007). In addition, the simulation contained a number of improvements in design and model numerics, including a deeper z-level structure in weakly stratified regions for improved simulation of deep convection and, later in the simulation, a new time-stepping scheme implemented by Remy Barrialle's group at SHOM in France that allowed a >2x increase in the timestep. Several simulation segments were run to test changing from ρ (density) and S advection to T & S advection, the new stepping scheme, and a modification to the QuikSCAT correction in the northern tropical Pacific. All of the preceding were implemented in the real-time global HYCOM/NCODA prediction system as soon as they were proven, except for the QuikSCAT correction to the atmospheric forcing and the associated mean SSH. The simulation was run for a total of 21 years, 15 years beyond initialization from climatology, with some years repeated to test changes. It was run on 1388 processors of a Cray XT3 at the Environmental Research and Development Center in Vicksburg, MS and required 6 wallclock hrs/model month using the increased timestep.

RESULTS

Evaluation of ocean model simulations without data assimilation is essential because ocean model simulation skill is critical to dynamical interpolation skill in ocean data assimilation and to model forecast skill, the latter lasting ~1 month for mesoscale variability because it is largely a nondeterministic response to atmospheric forcing in deep water, except in the surface boundary layer. In addition, ocean model simulation skill is essential in representing ocean features that are insufficiently observed (e.g., mixed layer depth and other subsurface features) and for converting atmospheric forcing and topographic/coastline constraints into oceanographic information, critical in the surface boundary layer, shallow water and the equatorial wave guide (Hurlburt et al., 2007).

Overall, the QuikSCAT correction to the atmospheric forcing had a clear positive impact on the 1/12° global HYCOM simulation, as did most of the other improvements described in the preceding section. Examples include much improved circulation patterns in the Indonesian throughflow region and the Japan/East Sea, elimination of the excessively strong South Equatorial Countercurrent (SECC) which crossed much of the South Pacific (a flaw illustrated in the Hurlburt (2006) ONR Report), a stronger and more realistic western boundary current in the North Atlantic, and more realistic mean pathways for the Kuroshio and Gulf Stream, the latter illustrated in Fig. 1a. The Gulf Stream 4-year mean pathway is the best obtained from a non-assimilative HYCOM global or Atlantic simulation to date, but still is not sufficiently inertial, e.g. the drop in mean SSH from the south to north side of the stream at 68°W is 75 cm vs. an observed drop of 105 cm shown in Chassignet and Marshall (2007). Fig. 1b shows the latest comparison (5 October 2007) between the operational IR frontal analysis of the Gulf Stream northwall pathway from NAVOCEANO and the Gulf Stream pathway from a real-time 1/12° global HYCOM/NCODA nowcast.

Fig. 2 shows a statistical analysis of temperature error as a function of depth between 1/12° global HYCOM and observations, performed in collaboration with a 6.4 project. A series of thirty 4-day 1/12° global HYCOM forecasts, spanning the period June-July 2007, are used. Each was initialized from the pre-operational system. Forecast simulations were only run for those dates with four days of atmospheric forecast forcing. A total of 8007 temperature profiles from fixed buoys and ARGO floats (fairly evenly distributed between 65°S-47°N) have been assimilated into HYCOM. The black curve represents the analysis time while the red line represents the 4-day forecast, thus degradation of the forecast is noted by the spread between the two curves. Maximum bias (left) and root-mean-square-error (center) occur near 100 m depth, indicative of error in simulating the mixed layer depth. Skill score is relatively high at all depths.

Figs. 3-4 contain results of evaluations performed on 1/12° global HYCOM/NCODA hindcasts and 30-day forecasts initialized from the hindcasts. The hindcasts are discussed in the Chassignet et al. (2007) ONR Report.

Fig. 3 and Table 1 provide a visual and quantitative comparison of eddies seen in an unusually cloud-free SeaWiFS ocean color image and HYCOM in the NW Arabian Sea and Gulf of Oman for 6 October 2002. The image shows numerous eddies, ranging in diameter from 1/4° to >2°. Twenty of these with clearly defined eddy centers are numbered in order of decreasing eddy size. The first four are ~2° or more in diameter, eddies 5-8 ~1°, 12-16 ~1/2° and 17-20 ~1/4°. Eddies 11-20 with diameters of 25-75 km are designated as small eddies. During that time HYCOM assimilated altimeter data from ERS-2, GFO and Jason-1. Model dynamical interpolation skill is required to map such small eddies and model-independent analyses have only demonstrated skill for eddies >75 km (Ducet et al., 2000). In Table 1, HYCOM mapped 80% of the eddies, 90% of the 10 largest and 70% of the small eddies with median eddy center location errors of 50 km, 68 km and 44 km respectively.

Fig. 4 shows the skill of 30-day forecasts of SSH initialized from HYCOM/NCODA hindcasts over the world ocean, 45°S-45°N, and over five subdomains (defined in Table 2) using anomaly correlation as the metric, a metric where .6 represents the minimum useful forecast skill. The NW Arabian Sea and Gulf of Oman subdomain is similar to the one used in Fig. 3. Results of three forecasts are plotted for each subregion, (1) persistence in blue (a forecast of no change), (2) a forecast with analysis quality forcing for the duration (green line) and (3) a forecast with five days of forecast forcing (here analysis quality) followed by 25 days where the atmospheric forcing reverts toward climatology (red line). The model forecasts are more accurate than persistence in all subregions. Except for the Yellow Sea, all show relatively low sensitivity to the quality of the atmospheric forcing because, on the forecast time scale, the forecast evolution is largely a non-deterministic response to the atmospheric forcing due to flow instabilities that generate eddies and current meanders (e.g. Figs. 1b and 3). Thus, the forecasts are more sensitive to errors in the initial state than in the atmospheric forcing. However, the opposite is true in shallow water and surface boundary layers, as illustrated for the Yellow Sea (Fig. 4f), a shallow water marginal sea.

IMPACT/APPLICATIONS

HYCOM with data assimilation is on track for use in an operational eddy-resolving, fully-global ocean prediction system. It will provide boundary conditions to finer resolution coastal/regional models that may use HYCOM or a different model. HYCOM is designed to make optimal use of three types of vertical coordinate, isopycnal, σ and pressure (~z-level). Isopycnals are the natural coordinate in stratified deep water, terrain-following (σ) coordinates in shallow water and z-levels within the mixed layer. The layered continuity equation allows a smooth dynamical space and time varying transition between the coordinate types. HYCOM permits isopycnals intersecting sloping topography by allowing zero thickness layers and it should allow accurate transition between deep and shallow water, historically a very difficult problem for ocean models. It also allows high vertical resolution where it is most needed, over the shelf and in the mixed layer. The isopycnal coordinate reduces the need for high vertical resolution in deep water. The project is represented by E. Chassignet (Florida State), J. Cummings (NRL) and H. Hurlburt (NRL) on the International GODAE Steering Team, a multinational effort designed to help justify a permanent global ocean observing system by demonstrating useful real-time global ocean products.

TRANSITIONS

None

RELATED PROJECTS

This is a highly collaborative NOPP project with 24 partnering groups listed in the proposal. These partners are universities (with Eric Chassignet at Florida State as the overall lead PI), government (Navy and NOAA), industry and international. Partnering projects at NRL include 6.1 Global Remote Littoral Forcing via Deep Water Pathways, 6.1 Coupled physical and bio-optical processes in the Coastal Zone, 6.2 NOPP – HYCOM Coastal Ocean Hindcasts and Predictions: Impact of Nesting in

HYCOM GODAE Assimilative Hindcasts, 6.3 Battlespace Environments Institute – ESMF for Atmospheric-Ice-Ocean Coupling and Component Interoperability, 6.4 Large Scale Ocean Modeling, 6.4 Ocean Data Assimilation and 6.4 NPOESS/Mesoscale Oceanography. Additionally, the project received grants of HPC time from the DoD High Performance Computing Modernization Office, including an FY05-08 HPC challenge grant entitled "Global Ocean Prediction using HYCOM" on the IBM SP4+ and SP5 at the Naval Oceanographic Office at Stennis Space Center, MS and the Cray XT3 at the Environmental Research and Development Center (ERDC) in Vicksburg, MS. This project is represented on the International GODAE Steering Team by E. Chassignet (Florida State), J. Cummings (NRL) and H. Hurlburt (NRL). See related ONR reports for this project by Chassignet at al., Pullen and Kindle and by Weisberg et al.

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Table 1: Eddy center location errors in 1/12° global HYCOM/NCODA compared to ocean color from SeaWiFS in the northwestern Arabian Sea and Gulf of Oman

Ocean color eddy ID#	A or C	Ocean color eddy center location °N	°E	1/12° HYCOM eddy center location error in km	Ocean color eddy ID#	A or C	Ocean color eddy center location °N	°E	1/12° HYCOM eddy center location error in km
1	C	23.55	60.2	48	**11**	C	23.7	62.3	52
2	A	18.3	62.0	48	**12**	C	19.3	58.8	65
3	A	21.15	60.25	37	**13**	A	19.225	59.35	26
4	C	19.65	60.4	59	**14**	A	25.3	58.55	28
5	C	16.8	55.65	72	**15**	C	24.1	61.75	NP
6	C	17.0	58.9	68	**16**	C	22.25	62.7	48
7	C	16.7	57.9	97	**17**	C	23.1	62.55	44
8	A	18.0	57.6	68	**18**	A	22.5	62.85	NP
9	C	25.1	57.6	76	**19**	C	22.05	62.05	NP
10	A	24.7	62.5	NP	**20**	C	22.2	59.95	22

% of eddies present in the model		**Median eddy center position error in km**	
All eddies	80%	All eddies	50
Large eddies, 1-10	90%	Large eddies	68
Small eddies, 11-20	70%	Small eddies	44

Notes:

The ocean color eddy ID numbers are plotted on Figure 3a. Eddies are listed in order of decreasing size as depicted by the ocean color. Eddy position measurement error is 10-15 km in both the ocean color and the models.

A, C: A for anticyclonic eddies, C for cyclonic eddies

NP: eddy not present

Table 2: Subregions depicted in Figure 4.

Subregion	Latitude range	Longitude range
World Ocean	45°S - 45°N	all
Gulf Stream region	35°N - 45°N	76°W - 40°W
Equatorial Pacific	20°S - 20°N	109°E - 77°W
NW Arabian Sea and Gulf of Oman	15°N - 26°N	51°E - 65°E
Hawaiian Islands	18°N - 23°N	159.5°W - 153.5°W
Yellow and Bohai Seas	30°N - 42°N	118°E - 127°E

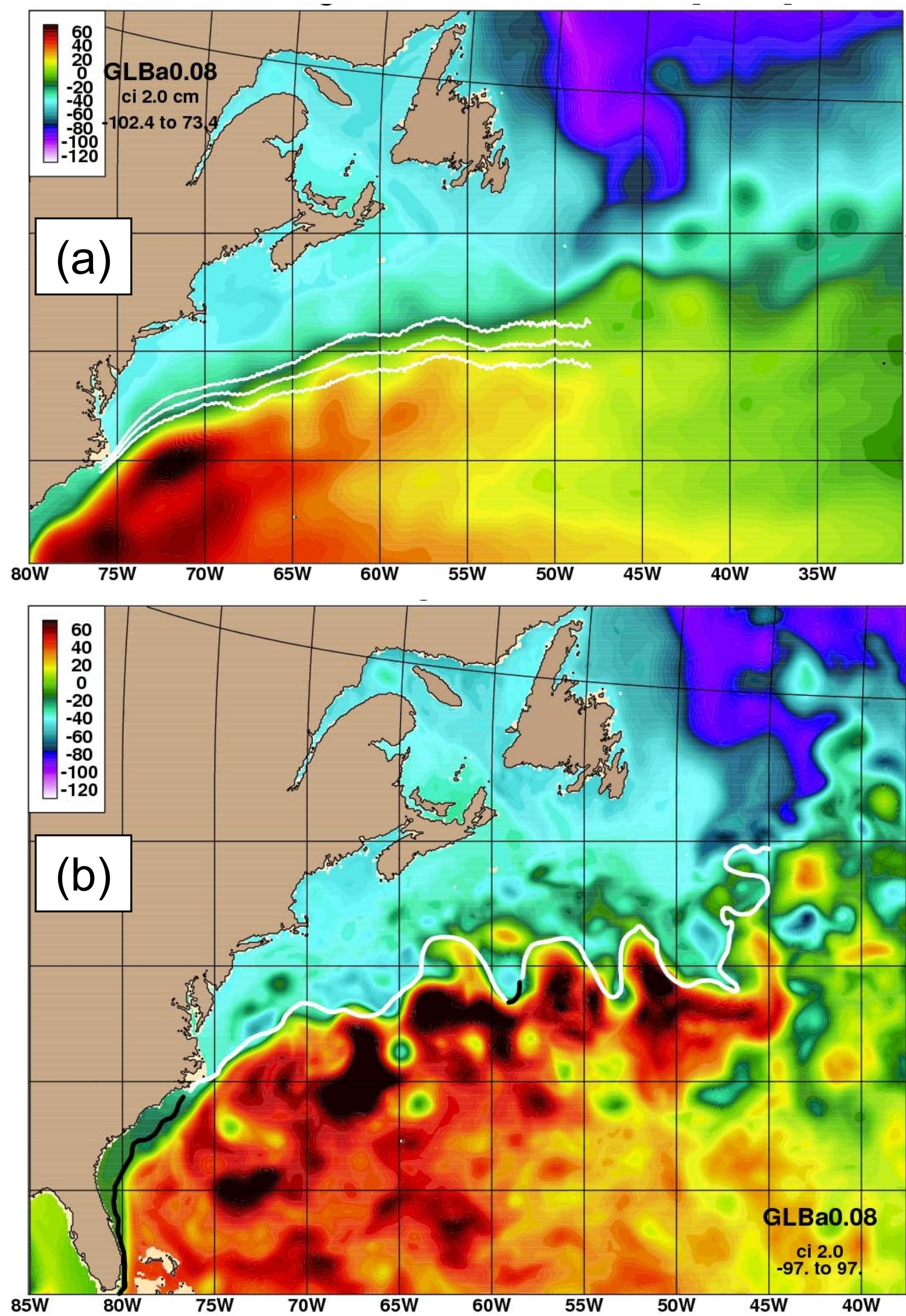

Figure 1: (a) Mean SSH over four model years from non-assimilative 1/12° global HYCOM using climatological wind and thermal forcing from the European Centre for Medium-Range Weather Forecasts with wind speed corrected using a QuikSCAT climatology. White overlaid lines are the mean position of the IR northwall ± one standard deviation by Cornillion and Sirkes (unpublished). (b) Sea surface height (SSH) in the Gulf Stream region on 5 October 2007 from the pre-operational 1/12° global HYCOM/NCODA nowcast/forecast system running daily in real-time at NAVOCEANO. An independent frontal analysis based on satellite sea surface temperature is overlaid. White (black) line segments are for data newer (older) than four days.

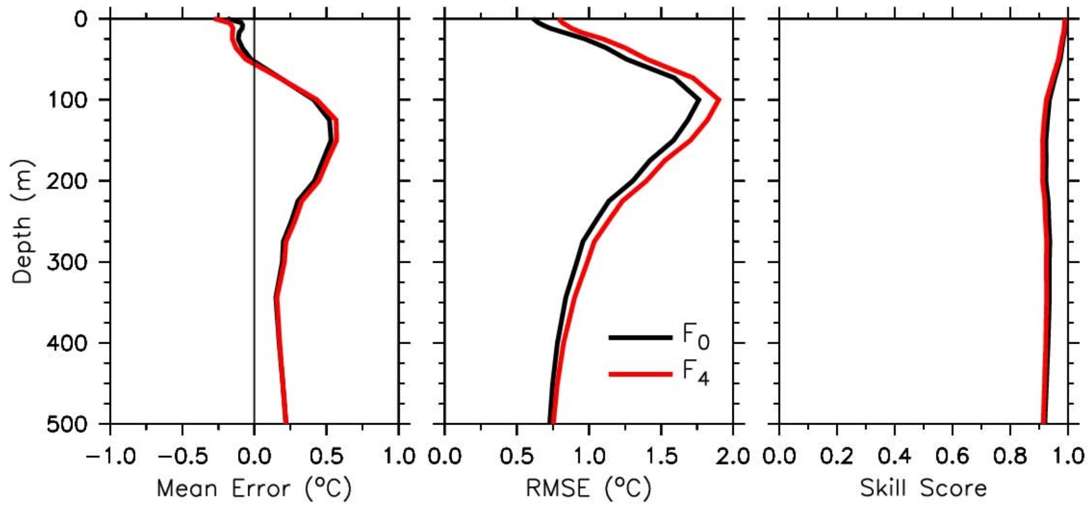

Figure 2: (left) Mean temperature error (°C), (middle) root mean square error (°C) and (right) skill score as a function of depth (upper 500 m) for the (black line) analysis field and (red line) 4-day forecast from a series of thirty forecasts from 1/12° global HYCOM/NCODA spanning the period June and July 2007. A total of 8007 profiles from fixed buoys and ARGO floats were used in this analysis. For each forecast run, the model was initialized from the pre-operational system running at NAVOCEANO.

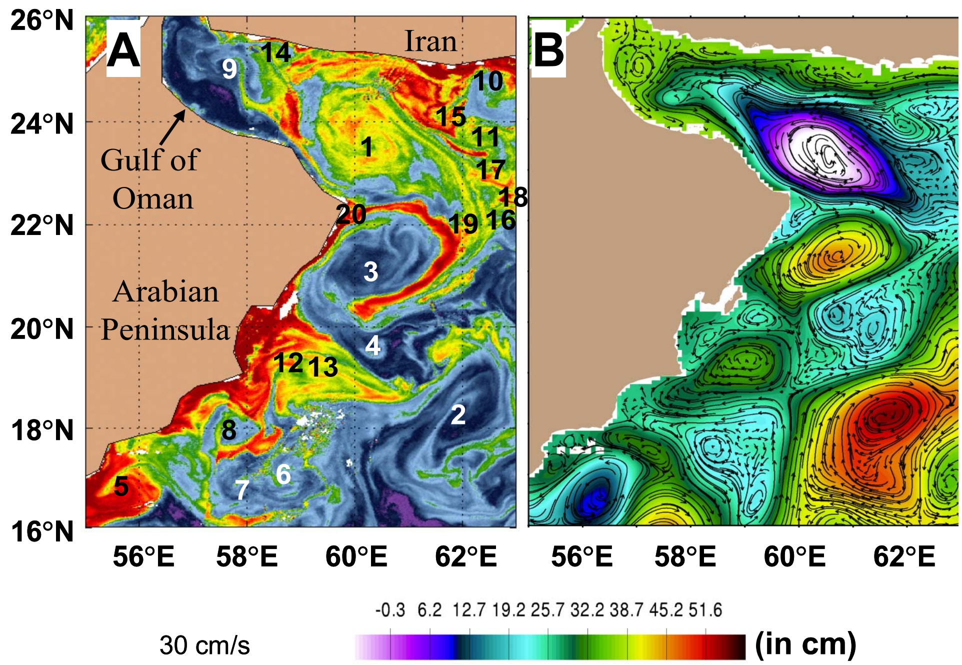

Figure 3: A comparison of eddies and currents seen in (a) chlorophyll concentration from SeaWiFS (2-6 October 2002 latest cloud free pixel composite with most data on 6 October) with (b) data-assimilative HYCOM/NCODA nowcast SSH and currents. In (a) eddies with clearly defined centers are numbered in order of decreasing size for use in Table 1. The color of the number varies only for visual clarity. Note a few of the smallest eddies are not visible due to limitations of plots, e.g. current vector subsampling.

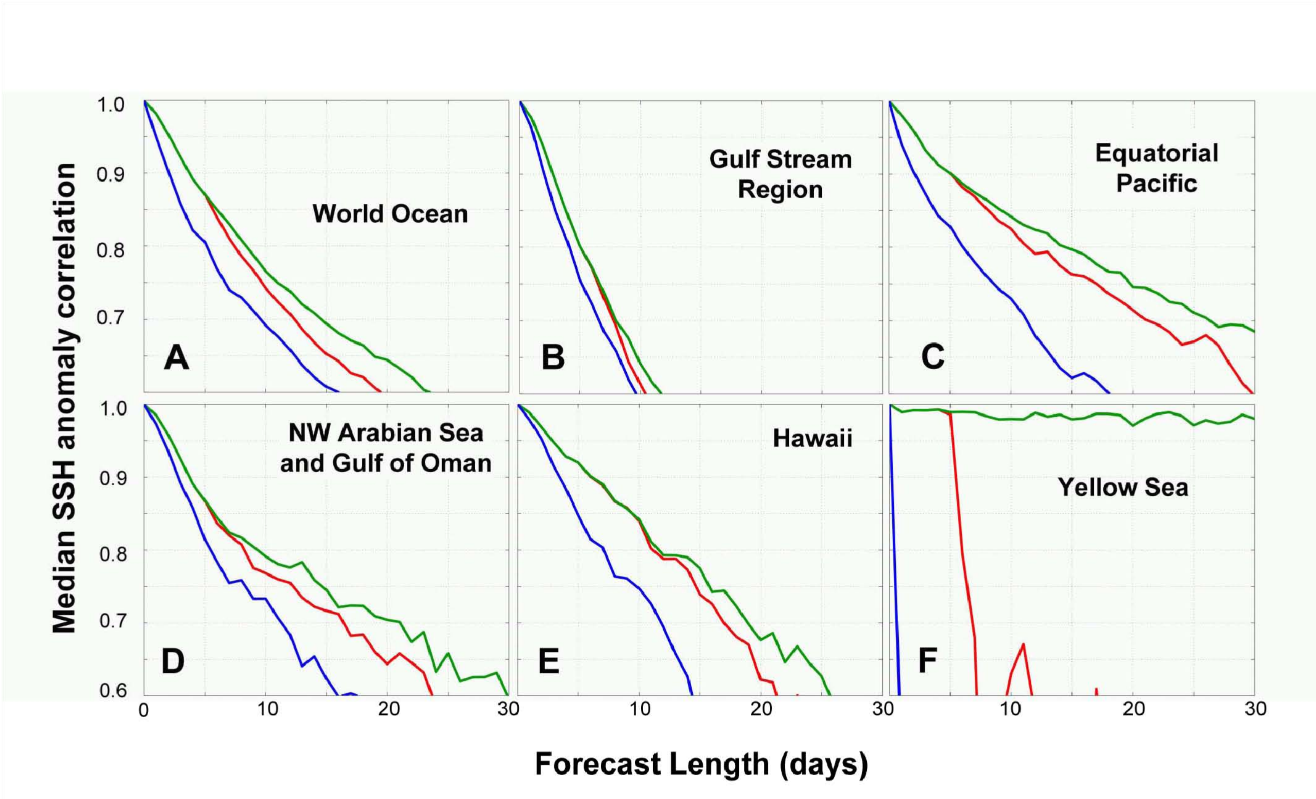

Figure 4: Verification of 30-day ocean forecasts, (a-f) median SSH anomaly correlation vs. forecast length in comparison with the verifying analysis for (a) global HYCOM/NCODA (45°S-45°N) and five subregions (b-f) defined in Table 2. The red curves verify forecasts using operational atmospheric forcing, which reverts toward climatology after five days. The green curves verify "forecasts" with analysis quality forcing for the duration and the blue curves verify forecasts of persistence (i.e. no change from the initial state). The plots show median statistics over twenty 30-day HYCOM forecasts initialized during January 2004 - December 2005, a period when data from three nadir-beam altimeters, Envisat, GFO and Jason-1, were assimilated.